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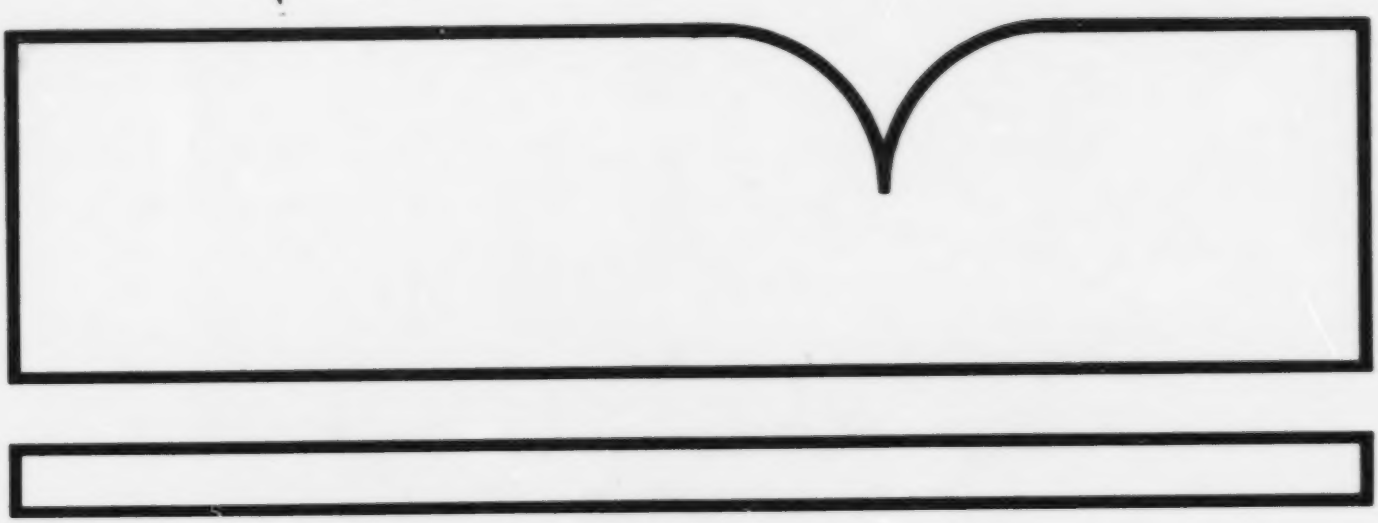

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A Five-Stage Cyclone System for in Situ Sampling

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■ This paper describes the development and calibration of a five-stage cyclone system for in situ sampling of process streams. Cyclones may be used to advantage for collecting large samples and in sampling aerosols of high particulate concentration. The cyclone system was calibrated using a vibrating orifice aerosol generator and a pressurized Collison nebulizer to disperse monodisperse latex particles. At 25 °C, 28.3 L/min, and for a particle density of 1.0 g/cm^3, the D_{50} cut points of the cyclone system were 5.4, 2.1, 1.4, 0.65, and 0.32 μm for cyclones numbered I–V, respectively. Results from calibrating the cyclones at several conditions of flow rate, temperature, and particle density suggest that the D_{50} cut points are: (a) proportional to the flow rate of the gas raised to a negative exponent that is between −0.63 and −1.11, (b) linearly proportional to the viscosity of the gas, and (c) proportional to the reciprocal of the square root of the particle density.

The majority of measurements to determine the particle-size distribution in process streams are made with cascade impactors. Impactors, however, have several limitations:

- When the mass concentration is high, the sampling time may be undesirably short.
- Considerable experience and skill are required to obtain valid data.
- Particle bounce and reentrainment cause an unpredictable, but significant, error in the stage and backup filter catches (*1*).
- Frequently there is not enough mass collected on some stages to be weighed accurately.
- Impactors are used with lightweight collection substrates, which are often unstable in mass when exposed to the process stream (*2*).
- There is not enough mass collected for chemical analysis of the particles in each size fraction.

A series of cyclones with progressively decreasing cut points will perform similarly to impactors, but without many of the associated problems. Cyclones, however, also have limitations to their applicability (*3*):

- There is no general theory to describe the performance of small cyclones under field test conditions.
- Sampling times may be undesirably long at sources where the mass concentration is low.

Thus, depending on the nature of the test aerosol, either impactors or cyclones may be preferred for a certain application.

This study was undertaken to develop and evaluate a system containing five cyclones and a backup filter in series. The cyclones were calibrated, using monodisperse aerosols, over ranges in temperature, flow rate, and particle density similar to those expected for field sampling.

Background

Several theories have been suggested that attempt to predict cyclone behavior. Typically, the theories are based on the classical equation for centripetal force and include additional terms to describe effects such as viscous drag and turbulent

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16. ABSTRACT The paper describes the development and calibration of a five-stage cyclone system for in situ sampling of process streams. Cyclones may be used to advantage for collecting large samples and in sampling aerosols of high particulate concentration. At 25 C, 28.3 L/min, and for a particle density of 1.0 g/cu cm, the D50 cut points of the cyclone system were 5.4, 2.1, 1.4, 0.65, and 0.32 micrometers for cyclones I-V, respectively. Results from calibrating the cyclones at several flow rates, temperatures, and particle densities suggest that the D50 cut points are: (1) proportional to the flow rate of the gas raised to an exponent between -0.63 and -1.11, (2) linearly proportional to the viscosity of the gas, and (3) proportional to the reciprocal of the square root of the particle density.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Sampling	Stationary Sources	14B
Cyclone Separators	Five-stage Cyclone	07A,13I
Particles		14G
Aerosols		07D
Dust		11G

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flow of the gas in the cyclone. The final equation usually gives the cyclone's collection efficiency in terms of the cyclone's dimensions and various parameters of the test aerosol.

Cyclone behavior may be expressed conveniently in terms of a D_{50}, the diameter of the particle that is collected with 50% efficiency. One conventional theory, that of Lapple (*4*), gives the cyclone D_{50} as a square root function of several parameters:

$$D_{50} = \sqrt{\frac{9H_cB_c^2\mu}{2\pi N_e\rho Q}} \quad (1)$$

where H_c is the height of the cyclone inlet, B_c is the width of the cyclone inlet, D_{50} is the diameter of particles that will be collected with 50% efficiency, μ is the gas viscosity, N_e is the effective number of turns made by the gas stream in the cyclone, ρ is the density of the particles, and Q is the flow rate of the gas through the cyclone. For most conditions of cyclone experimentation, the gas viscosity is solely a function of temperature and gas composition, so that Lapple's theory gives the D_{50} in terms of easily measured variables: gas temperature, cyclone inlet dimensions, gas flow rate, and particle density. Unfortunately, because of the complicated flow patterns in cyclones, N_e is difficult to predict or measure.

Leith and Licht's (*5*) cyclone theory suggested a somewhat different equation for cyclone D_{50}'s:

$$D_{50} = \left[\left(\frac{18DB_cH_c}{E(n+1)}\right)\left(\frac{\mu}{Q\rho}\right)(\ln\sqrt{2})^{2n+2}\right]^{1/2} \quad (2)$$

where D is the diameter of the cyclone body, E is a cyclone geometry coefficient dependent on the cyclone's dimension ratios only, and n is a parameter that depends on the cyclone diameter and the gas temperature.

This equation includes the same $\sqrt{\mu/Q\rho}$ term as did Lapple's equation, but it also contains the variable n, which is dependent on the gas temperature. Thus, as the gas temperature changes, the D_{50} will not be a simple square-root function of the gas viscosity.

The theories of Lapple, and Leith and Licht, although developed for larger cyclones, provide a basis for comparison of recent small cyclone experimental data. Other cyclone theories are discussed by Leith and Mehta (*6*) and by Chan and Lippmann (*7*).

Experimental work reported by Chan and Lippmann (*7*) indicated that the D_{50} of a cyclone does not have an inverse square-root dependence on the sample flow rate. In fitting an equation of the form $D_{50} = KQ^n$ to experimental data, they found n to be between −0.636 and −2.13 for several cyclones. Also, for one cyclone, two distinct flow rates gave the same D_{50}. Hochstrasser (*8*) found a similar hysteresis-type effect in the pressure drop/flow rate relationship in several cyclones and hypothesized that this was due to the flow in the outlet pipe being laminar in one case and turbulent in the other, depending on whether the flow rate was being increased or decreased.

Work reported by Cushing et al. (*9*) on the calibration of the middle cyclone of the EPA source assessment sampling system (SASS) included data taken at two particle densities and three values of gas viscosity. These data: (a) verify the theory that a cyclone D_{50} is inversely proportional to the square root of the particle density, which comes directly from Stokes law, (b) indicate that the experimental relationship between D_{50} and gas viscosity (or temperature) is not square root, but linear, and (c) also indicate that D_{50} vs. flow rate is not a square-root relationship.

Technical Discussion

Cyclone Design. Figure 1 shows the five-stage cyclone system. The system is designed to operate instack at a sample flow rate of 28.3 L/min, and is compact enough to fit through a 10-cm diameter port. The design objective was to obtain five D_{50}'s equally spaced on a logarithmic scale within the range of 0.1–10 μm. Since there is no theory that is sufficiently accurate to serve as a basis for small cyclone design, the dimensions were selected to be identical or related to those of cyclones that had been previously evaluated (*3*). Some redesign based upon trial and error was required to achieve the desired performance.

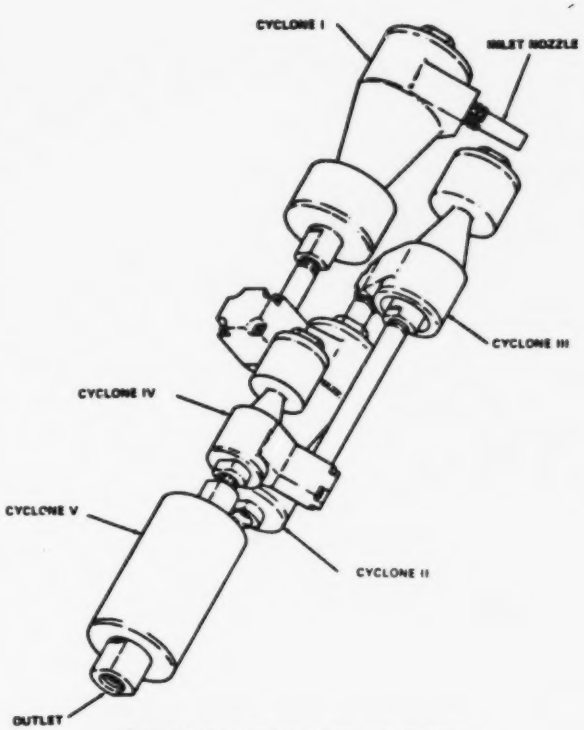


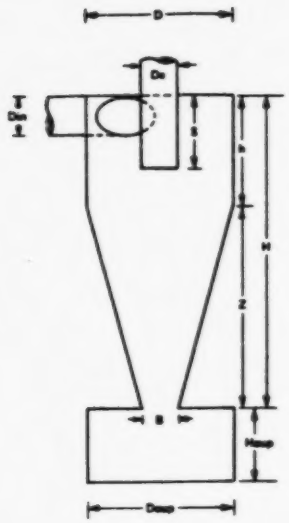
Figure 1. The five-stage cyclone system

The cyclones are numbered sequentially I through V, starting with the largest. Cyclones II–V are of conventional design, as shown in Figure 2. Cyclone I is somewhat different, with the gas exit tube passing through the collection cup (*10*). The critical cyclone dimensions are summarized in Figure 2.

Experimental Procedures. Two aerosol generator systems were used to calibrate the cyclones. A vibrating orifice aerosol generator with a heated transfer line was used to produce dye particles 1.2–8.0 μm in diameter. A Collison nebulizer system was employed to disperse latex spheres of 0.3–2.0 μm diameter.

The vibrating orifice aerosol generator (VOAG) used in this study is similar to that developed by Berglund and Liu (*11*) and has been described previously by Cushing et al. (*12*). The two types of dye particles were ammonium fluorescein (density 1.35 g/cm^3) and Du Pont Pontamine Fast Turquoise 8GLP dye (density 2.04 g/cm^3). All of the internal surfaces of the cyclones were washed after sampling, and the mass collected by each cyclone was determined by absorption spectroscopy.

The second aerosol generator was a pressurized Collison nebulizer, which was used to disperse polystyrene latex (PSL) particles with diameters from 0.312 to 1.099 μm and with a density of 1.05 g/cm^3, and poly(vinyltoluene) particles with diameters of 2.02 μm and with a density of 1.027 g/cm^3 (*13*). A general description of the system was given by Calvert et al. (*14*), and a more specific description by Cushing et al. (*12*). Particle concentrations at the inlet and outlet of the cyclone under test were measured with a Climet Model 208A particle



DIMENSIONS (CENTIMETERS)

CYCLONE	D	Dw	Dx	B	H	h	Z	S	Hasp	Dasp
I	4.47	1.27	1.50	1.66	6.95	2.24	4.71	1.57	2.25	4.46
II	3.66	1.01	1.06	1.29	6.82	2.11	4.71	1.57	2.22	3.73
III	3.11	0.75	0.83	0.76	4.91	1.40	3.51	1.08	2.22	3.10
IV	2.54	0.51	0.56	0.51	3.32	1.03	2.29	0.58	2.22	2.62
V	1.52	0.30	0.36	0.51	1.78	0.47	1.29	0.43	2.38	1.98

Figure 2. Summary of the cyclone dimensions

Table I. Laboratory Calibration of Five-Stage Cyclone System Test Conditions

flow rate, L/min	temp, °C	aerosol material used, cyclone I	II	III	IV	V
7.1	25				T/P[a]	P
14.2	25	T	T	T/A[a]	P	P
28.3	25	T	T	T/P	P	P
28.3	93	T	T	T		
28.3	204	T	T	T		

[a] T, turquoise dye particles; A, ammonium fluorescein particles; P, poly(styrene) latex or poly(vinyltoluene) particles.

counter. Because of the low melting point of the latex spheres, cyclones IV and V were calibrated at 25 °C only.

Table I lists the experimental parameters for the laboratory calibration study. As previously stated, three values each of flow rate, particle density, and gas temperature were selected, to include conditions that might be expected in field use. The objective of the experiments was to accurately determine the D_{50}'s of the cyclones by measuring the collection efficiency for particle diameters near the D_{50}.

Experimental Error

In tests conducted with particles generated by the VOAG, each point on the collection efficiency graphs represents the entrance of a very large number (over 10^7) of monodisperse particles into the cyclone inlet. The reproducibility of each point was found to be within 1 or 2% of the initial value of the collection efficiency, except for particle diameters very close to the D_{50} where the efficiency curve is almost vertical. The sample flow rate, as measured by the metering orifice, was accurate to within 1 L/min. The temperature of the dye aerosol was accurate to within 3 °C. The density of the particles was accurate to within 0.05 g/cm^3, and the reported size is estimated to be within 1%.

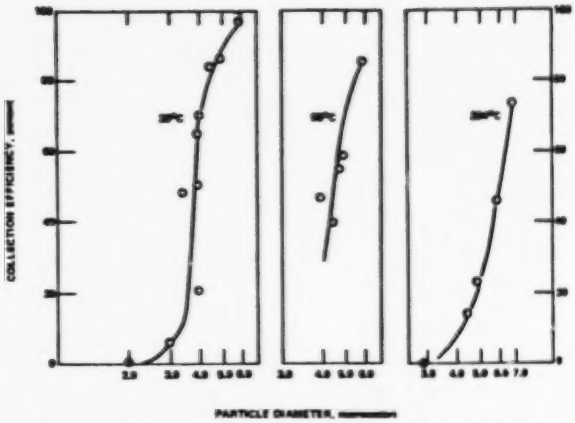


Figure 3. Collection efficiency of cyclone I at a flow rate of 28.3 L/min, temperatures of 25, 93, and 204 °C, and for a particle density of 2.04 g/cm^3

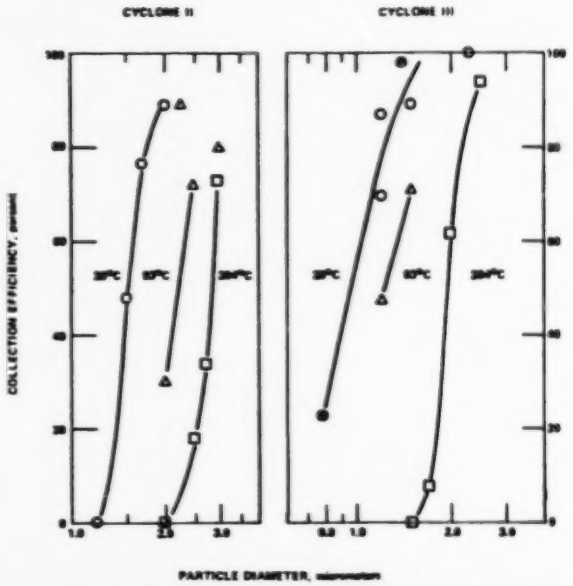


Figure 4. Collection efficiency of cyclones II and III at a flow rate of 28.3 L/min, temperatures of 25, 93, and 204 °C, and for a particle density of 2.04 g/cm^3. Solid symbols: derived from data taken at a particle density of 1.05 g/cm^3

For tests conducted with the Collison system, the aerosol concentration was approximately 10–40 particles/cm^3. Samples of 1-min duration were run alternately through the cyclone and a bypass line to a particle counter. At least five sets of inlet/bypass data were averaged to calculate each point shown in the graphs of collection efficiency vs. particle diameter. The flow rate was measured by an electronic mass flowmeter that is accurate to within 1 L/min. The temperature was stable to within 1 °C. The density of the latex particles is reported to be accurate to three significant digits. Particle size standard deviations were less than 0.0082 μm for sizes smaller than 2 μm in diameter and 0.0135 μm for the 2.020-μm diameter particles (*13*). The average standard deviation of the collection efficiency was 5% except for particle diameters very close to the D_{50}.

In order to avoid errors due to electric charges residing on the generated particles, α particle sources (500 μCi of ^{210}Po) were placed in the drying chamber of each aerosol generator. Separate tests verified that these sources effectively neutralized the aerosol.

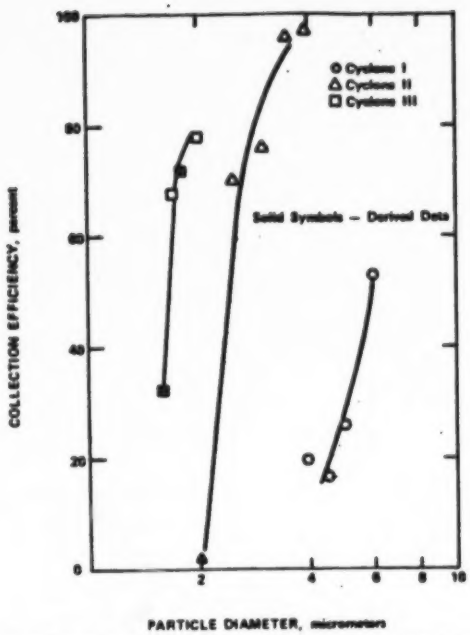


Figure 5. Collection efficiency of cyclones I, II, and III at a flow rate of 14.2 L/min, a temperature of 25 °C, and for a particle density of 2.04 g/cm³. Solid symbols: derived from data taken at a particle density of 1.35 g/cm³

Table II. Pressure Drop at a Mass Flow Rate of 28.3 L/min

cyclone[a]	pressure drop across cyclone	% of total pressure drop	inlet flow, L/min
I	5.1 mmH_2O	0.22	28.3
II	40.6 mmH_2O	1.76	28.8
III	71.1 mmH_2O	3.07	28.9
IV	332.7 mmH_2O	14.37	29.1
V	137.2 mmHg	80.58	30.1
total	170.2 mmHg	100.00	

[a] Barometric pressure = 747 mmHg. Ambient temperature = 25 °C.

Table III. Values of *K* and *n* for the Five-Stage Cyclone System

	cyclone				
	I	II	III	IV	V
n	−0.63	−0.70	−0.84	−0.98	−1.11
K	44.6	22.2	22.7	17.6	14.0

Results

The collection efficiency curves for cyclones I, II, and III, calibrated at 28.3 L/min with turquoise dye particles at temperatures of 25, 93, and 204 °C, are shown in Figures 3 and 4. The steepness of the curves indicates the extent to which the cyclones will have ideal behavior at these conditions. In Figure 4, the solid symbols represent collection efficiencies measured using latex particles and the Collison system and are called derived data. Derived data are values of collection efficiency and D_{50} that were measured using particles of a different density than that listed on the graph and were then transposed to particle diameters of equivalent aerodynamic behavior and the same density as those listed, by means of Stokes law. Application of Stokes law yields:

$$D_2 = \left(\frac{\rho_1 C_1}{\rho_2 C_2}\right)^{1/2} D_1 \qquad (3)$$

where D_1 and D_2 are the diameters of particles of densities ρ_1 and ρ_2, respectively, that have the same aerodynamic behavior, and C_1 and C_2 are the slip correction factors for particles of diameters D_1 and D_2, respectively. Equation 3 must be solved by iteration to yield D_2 and C_2 from an initial value of D_1 and C_1.

As an example, in Figure 4, the collection efficiency of cyclone III was 23% for PSL particles 1.099 μm in diameter and with a density of 1.05 g/cm³. From Equation 3, the equivalent diameter for particles of 2.04 g/cm³ is 0.75 μm.

Figure 5 shows the collection efficiency curves for cyclones I, II, and III, calibrated at a flow rate of 14.2 L/min and a

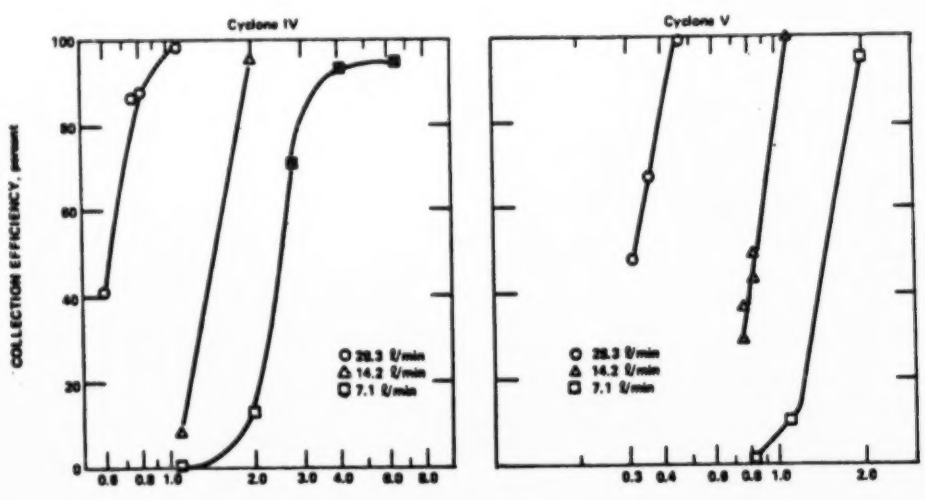


Figure 6. Collection efficiency of cyclones IV and V at flow rates of 7.1, 14.2, and 28.3 L/min, a temperature of 25 °C, and for a particle density of 1.05 g/cm³. Solid symbols: derived from data taken at a particle density of 2.04 g/cm³

Table IV. Laboratory Calibration of the Five-Stage Cyclone Sampler

flow, L/min	temp, °C	cyclone D_{50} cut points, [a] μm									
		I [b]		II [b]		III [b]			IV [b]		V [b]	
		2.64 [c]	1.00 [c]	2.64 [c]	1.00 [c]	2.64 [c]	1.35 [c]	1.00 [c]	1.00 [c]	1.00 [c]	1.00 [c]	1.00 [c]
7.1	25								2.5	(2.5)	1.5	(1.5)
14.2	25	5.9	(8.4)	2.4	(3.5)	(1.7)	2.1	(2.4)	1.5	(1.5)	0.85	(0.87)
28.3	25	3.8	(5.4)	1.5	(2.1)	0.95		(1.4)	0.64	(0.65)	0.32	(0.32)
28.3	93	4.4	(6.3)	2.3	(3.3)	1.2		(1.8)				
28.3	204	6.4	(9.1)	2.9	(4.1)	1.9		(2.8)				

[a] D_{50} cut points enclosed in parentheses are derived from the experimental data using Stokes law. [b] Cyclone. [c] Particle density, g/cm³.

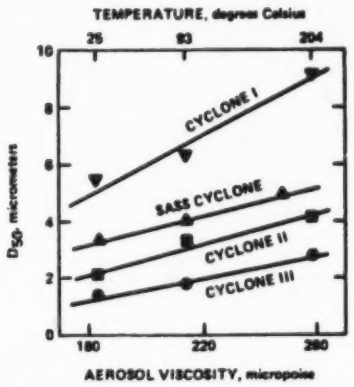


Figure 7. D_{50} vs. viscosity for cyclones I, II, and III at a flow rate of 28.3 L/min, temperatures of 25, 93, and 204 °C, and for a particle density of 1.00 g/cm³. SASS cyclone flow rate is 153 L/min

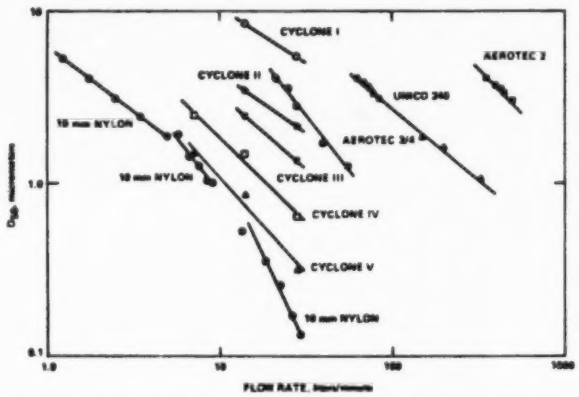


Figure 8. D_{50} vs. flow rate for cyclones I through V at flow rates of 7.1, 14.2, and 28.3 L/min, a temperature of 25 °C, and for a particle density of 1.00 g/cm³. Other cyclone data from Chan and Lippmann (*7*)

temperature of 25 °C with turquoise dye particles. The two derived data points were obtained using ammonium fluorescein. Again the steepness of the collection efficiency curves indicates that the cyclones have nearly ideal collection characteristics at the reduced flow rate of 14.2 L/min. In the collection efficiency curves for cyclone III, the transposed data taken using the ammonium fluorescein dye and the turquoise dye lie close to a single smooth curve and thus support the validity of applying Stokes law to transpose data from one equivalent diameter to another, based on density.

Figure 6 shows the collection efficiency curves for cyclones IV and V for a temperature of 25 °C and flow rates of 7.1, 14.2, and 28.3 L/min. The open symbols indicate data taken using either poly(styrene) latex particles or poly(vinyltoluene) particles. The solid symbols represent data taken using turquoise dye particles and translated to a density of 1.05 g/cm³ using Stokes law. Few calibration particle sizes were available in the range 1.0 to 2.8 μm, and the uncertainty in the values of the D_{50} that are within this size range is greater than for those that lie outside this size range.

The data cited above were for each of the cyclones sampling at the same actual inlet flow rates. However, when operating the cyclones as a series train, the inlet flow rate to each cyclone will be slightly different due to the pressure drops across the cyclones preceding it. In order to allow more accurate calculations of the cyclone D_{50}'s in field operation, the pressure drop was measured across each cyclone at the same mass flow with the inlet of the large cyclone operating at ambient pressure and temperature and at 28.3 L/min. The results of this measurement are listed in Table II.

Figure 7 shows the change in D_{50} due to the change in gas viscosity for cyclones I, II, and III and the EPA–SASS cyclone (*8*). Viscosity is dependent only on temperature for the calibration conditions, and the viscosity values 183, 214, and 259 μP correspond to 25, 93, and 204 °C, respectively. These values of viscosity were calculated from the equation:

$$\mu = \frac{T^{3/2}}{0.068T + 7.8} \qquad (4)$$

where μ is the viscosity in micropoise and T is the temperature in degrees Kelvin. Equation 4 is a curve fit to data given in the Handbook of Chemistry and Physics for the viscosity of air (*15*). For each cyclone, a linear regression has been performed on the three data points to give the best straight line. Although a search of the literature has not revealed a theory that suggests a linear dependence of D_{50} on viscosity, a straight line was suggested by the lack of a consistent trend in curvature of the data. The coefficient of determination is near unity for each set of data.

The change in D_{50} due to the change in gas flow rate, Q, for cyclones I through V and for four other cyclones as reported by Chan and Lippmann (*7*) is shown in Figure 8. Fitting the data to the equation $D_{50} = KQ^n$ yielded the values of K and n given in Table III. For the four cyclones of Chan and Lippmann, the range in values of n was −0.75 to −2.13, the magnitude of K ranged from 6.17 to 468.01, and the diameters of the cyclones ranged from 10 to 50 mm. The geometries and relative dimensions of the cyclones used by Lippmann and Chan (*16*) may not have been identical with each other or to the ones used in this study.

Summary

The five-stage cyclone system is an inertial particle sizing device that is designed for in situ sampling of industrial process streams. It will fit through a 10-cm diameter port and is equipped with nozzles of different diameters to allow isokinetic sampling at the nominal sample flow rate of 28.3 L/min.

The individual cyclones of the system were tested and calibrated in the laboratory under conditions similar to those frequently encountered in field tests: gas temperatures of 25, 93, and 204 °C, flow rates of 7.1, 14.2, and 28.3 L/min, and particle densities of 1.05, 1.35, and 2.04 g/cm^3. The D_{50}'s for the cyclone system at various operating conditions are given in Table IV. For laboratory test conditions the small cyclones have sharp collection efficiency curves, and thus the system should function adequately as a particle sizing device.

Data from this study (wherein different particle densities, ρ, were used) tend to support the D_{50} vs. $\rho^{-1/2}$ relationship suggested by several theories (*4, 17, 18*). On the other hand, the experimental results indicating that the D_{50}'s were directly proportional to the gas viscosity are in opposition to most theories (*4, 5, 17, 18*). Also, it was found in this study and others that the D_{50}'s of small cyclones are not inversely proportional to the square root of the flow rate as some theories predict (*7*). It appears that establishment of a definitive relationship between D_{50} and flow rate will require further investigation.

Acknowledgment

The mechanical design was done by David Hussey and part of the experimental data were taken by Don Johnson.

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